

Stability Analysis of Cut Slopes Using Continuous Slope Mass Rating and Kinematic Analysis in Rudraprayag District, Uttarakhand

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Abstract

In mountain terrains of Himalaya, road and highway networks play a vital role in remote areas for transportation, public network and all kind of socio-economic activities. The stability of rock slopes along the roads and highways is a major concern in these hilly regions. Any kind of slope failure may lead to disruption in traffic, loss of properties and lives/injuries as well as environmental degradation. The unplanned excavations of rock slopes for construction or widening purposes may undermine the stability of the slopes. The present study incorporates the stability analysis of road cut slopes along NH-109 which goes to holy shrine of Kedarnath. Slope failure is not only a phenomenon of rainy season but it has also been encountered even in dry season. The study area experiences high vehicular traffic especially from March to August due to pilgrims since it is the only road to Kedarnath. The distance of about 20 km between Rudraprayag and Agastmuni has been investigated. The continuous slope mass rating (CSMR) technique has been used for slope stability analysis at five different locations. CSMR is modification of original slope mass rating (SMR) proposed by Romana which is based on well established rock mass rating (RMR) technique. Kinematic analysis was also carried out to evaluate these sites for types of failure and its potential failure directions. The potentially vulnerable sites were identified. The results indicate that the CSMR technique may be exploited to assess the stability of rock slopes in the Himalayan territory.

Keywords: SMR, CSMR, RMR, Slope Stability, Rudraprayag

1. Introduction

Slope failure has been identified as one of the most frequent natural disasters that can lead to huge loss of property and lives. The Lesser Himalaya region is tectonically active zone characterized by a very complex structure of thrust sheets [1]. Slope failures are triggered by number of external factors like tectonic forces, weathering and erosion processes, and compounded-anthropogenic factors in the high relief mountain system [2]. Over the years, human activity has significantly contributed to an increase in slope failures in the Himalaya because of expansion of road networks, settlements and other development activities. The analysis of landslides is much complex as number of factors contributes in it. So the analysis requires quite large number of input parameters and also the analytical techniques are costly and time consuming.

The road networks are only way of communication in mountain regions of Himalaya. The stability problem of rock slopes along roads in the Himalaya is a major concern in most of the places. There are lots of major as well as minor landslides reported in hilly areas especially in monsoon season due to heavy rainfall and also in post-monsoon season. These slides are not limited to monsoon season but also being encountered in dry season in minor scales [3,4]. The unplanned excavation of rock slopes for road construction and widening makes the slopes vulnerable. The vibrations induced due to blasting may cause widening of fractures. The exposed rock mass in Himalaya, which is already deformed, with steeper cut slopes along roads may prone to failure. The failure of slopes may lead to distraction in traffic. Several cases of distraction in traffic are being reported that may create lots of difficulties to travelers as well as pilgrims of holy shrines of Kedarnath and Badrinath. Therefore, evalua-

tion of the stability situation along these roads and highways is imperative for safety and maintenance purposes.

There are several approaches of slope stability analysis are being used now days like limit equilibrium, analytical and kinematic, physical and numerical models [5-7]. One of the most widely used and adequate method is slope mass rating (SMR) technique [8,9]. SMR is based on the rock mass rating (RMR) technique given by Bieniawski [10,11]. RMR technique is based on detailed field and laboratory study which involves collection of data at site slopes, strength of rock exposed on slope face, condition of discontinuities, spacing of discontinuities, orientation of discontinuities, and ground water condition. SMR includes RMR along with some adjustment factors based on relation of joint orientation with slope and method of slope excavations. The adjustment factors in SMR technique, proposed by Romana, are discrete and are more decision based. The continuous SMR (CSMR) proposed by Tomas provides continuous determination and very less decision based [12-14]. The CSMR assigns unique value to each adjustment factor of slope that result into more accurate value of SMR [14].

The present study incorporates the assessment of road cut sections in Rudraprayag District, Uttarakhand, India. Field investigations have been carried out to study the lithological and structural variations in rock slopes between Rudraprayag and Agastmuni, about 20 km section along NH-109. Five locations were selected on the basis of exposures of the different lithology and the slope conditions. Slopes at these locations have been excavated by uncontrolled (or poor) blasting method for highway construction, were studied and analysed for their potential degree of stability using CSMR approach. Kinematic analysis has been performed for the line of intersection of two or more discontinuities, as the rocks are highly jointed in some parts of road cut sections. The kinematic analysis reveals the type and the possible direction of movement of failures along with identifying the potentially unfavourable joint planes.

2. The Study Area

The location of study area lies in Rudraprayag district, Uttarakhand, India. Rudraprayag is situated at the confluence of the Mandakini and the Alaknanda rivers, known in popular culture as the "Sangam". The town holds a prominent place as it is a stopover for the pilgrims and travelers to the world famous holy shrines of Badrinath and Kedarnath. From Rudraprayag, NH-109 and NH-58 split, the former going towards Kedarnath and the latter towards Badrinath. The study area comes under NH-109 which runs from Rudraprayag to Kedarnath along Mandakini river (**Figure 1**). The study area between Rudra-

prayag (N30°17'6.30"; E78°58'59") and Agastmuni (N30°23'34.5"; E79°1'42.4") comes under toposheet numbers 53J/15 and 53N/3 of the Survey of India toposheets.

3. Geological Setting

The study area comes in Garhwal group of lesser Himalaya and comprises diverse rock types ranging in age from Paleoproterozoic to Mesoproterozoic (**Figure 2**). The Main Central Thrust (MCT) and Almora Thrust mark the boundary of Garhwal group [15]. It consists of thick succession of low grade meta-sediments made up of quartzite along with penecontemporaneous metabasics and carbonate rocks. The Garhwal group has been divided into five formations as the Uttarkashi, Khattukhal, Rautgara, Deoban and Berinag formations in an ascending order. The rocks of Garhwal group were intruded by acid and basic igneous rocks [16]. The Garhwal group has been undergone three phases of tectonic deformations [15].

Mehdi *et al.* [17] and Kumar and Agrawal [15] were probably first to formulate the geology of the area. Negi *et al.* [18] have given the detailed report on geology and structure of Rudraprayag-Tilwara-Mayali area. The rock types exposed in the study area are Rudraprayag metavolcanics, Haryali quartzites, Tilwara quartzites, Tilwara metavolcanics, epidiorites and Rampur chlorite phyllites. Rudraprayag metavolcanics are massive and jointed in rock mass with quartz, pyroxene, plagioclase, epidote as mineral constituents. Quartz veins as infilling along joints are exposed 1 Km north from Rudraprayag.

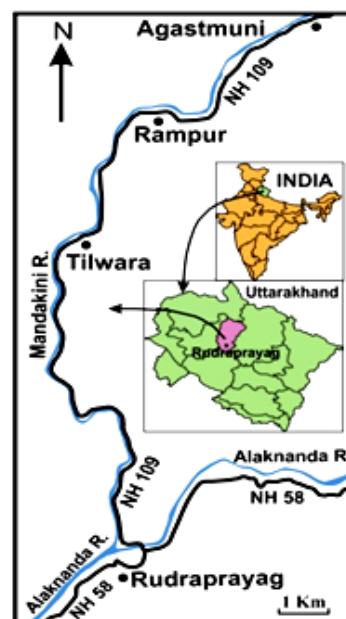


Figure 1. Location map of study area.

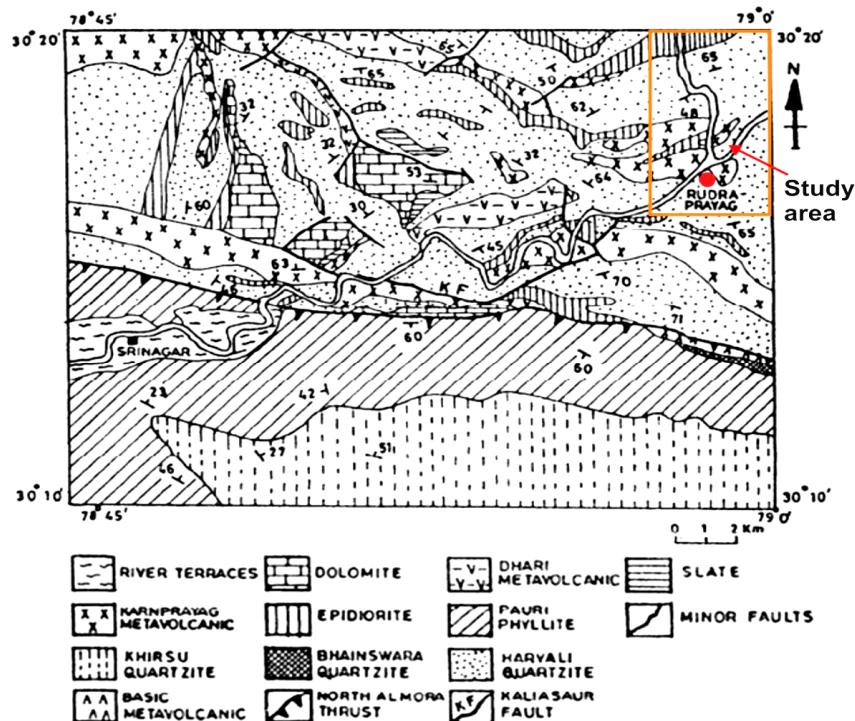


Figure 2. Geological map of the area (after Kumar and Agrawal [15]).

Haryali quartzite as named by Kumar and Agrawal [15] is very less metamorphosed, thick bedded, varying white to purple/pink in colour and well exposed between Rudraprayag and Tilwara. Along the joint planes, jasper, chert and talc occur as infilling material. Tilwara metavolcanics, light to very dark green in colour, are more metamorphosed and deformed than the Rudraprayag metavolcanics. It is mainly composed of feldspar and pyroxene which are altered. Tilwara quartzites are different than Rudraprayag/Haryali quartzite as are thin bedded, highly deformed and metamorphosed. In the east of Tilwara, the quartzites are metamorphosed into talc-quartzites and towards Rampur, the Tilwara quartzites are mainly of schistose type. The most of the formations of the study area have been intruded by sills and dykes of dolerite which have later been metamorphosed into epidiorite. Hornblende and plagioclase are the major mineral constituents with hornblende altering into chlorite and biotite, ilmenite, epidote as minor constituents. The light to dark green colour friable chlorite phyllite/schist is best exposed on the right flank of the Mandakini River near Rampur.

4. Method

Field investigations have been carried out to study the attitude of excavated slopes and measurements of discontinuities present in the rock mass accompanied by collection

of representative samples. Laboratory experiments have been performed to evaluate the strength parameters as per ISRM suggested methods [19,20]. The continuous SMR (CSMR) technique has been used to classify the rock slopes at five different locations. CSMR is modification of discrete SMR technique of Romana which is based on Bieniawski's RMR technique. The SMR system provides adjustment factors, field guidelines and recommendations on support methods which allow a systematic use of geomechanical classification for slopes. The CSMR provides unique value of each adjustment factor unlike a range as in SMR.

RMR is computed according to Bieniawski's [10] proposal, adding rating values for five parameters: i) Strength of intact rock, ii) RQD (measured or estimated), iii) Spacing of discontinuities, iv) Condition of discontinuities, and v) Water inflow through discontinuities. RMR has a total range of 0 - 100 (**Table 1**).

The slope mass rating (SMR) proposed by Romana [8] is obtained from RMR by subtracting a factorial adjustment factor depending on the joint-slope relationship and adding a factor depending on the method of excavation

$$\text{SMR} = \text{RMR} - (F_1 \cdot F_2 \cdot F_3) + F_4$$

The CSMR is also computed using an equation which is similar to discrete SMR, but the difference lies in calculating the adjustment factors (F_1 , F_2 and F_3) which are depending on the joint-slope relationship. The factor F_4 ,

Table 1. Rock mass classification (after Bieniawski [10]).

Parameter		Ranges of Values						
UCS	Values	> 250 MPa	100-200 MPa	50-100 MPa	25 - 50 MPa	5 - 25	1 - 5	< 1 MPa
	Rating	15	12	7	4	2	1	0
RQD	Values	90 - 100%	75 - 90%	50 - 75%	25 - 50%			25%
	Rating	20	17	13	8			3
Joint Spacing	Values	> 2 m	0.6 - 2.0 m	200 - 600 mm	60 - 200 mm			< 60 mm
	Rating	20	15	10	8			5
Joint Condition	Values	Very rough surfaces No continuous No separation Unweathered wall	Slightly rough surfaces Separation < 1mm Slightly weathered wall	Slightly rough surfaces Separation < 1mm. Highly weathered wall	Slickensided surfaces OR gauge < 5 mm thick OR separation 1-5 mm	Soft gauge > 5 mm OR Separation > 5 mm Continous		
	Rating	30	25	25	25			0
Groundwater	Values	Completely dry	Damp	Wet	Dripping			Flowing
	Rating	15	10	7	4			0

depending on the method of excavation is same for discrete SMR as well as CSMR.

The adjustment rating for discrete SMR is the product of three factors proposed by Romana [8] as follows:

(i) F_1 depends on parallelism between joints and slope face. Its range is from 1.00 to 0.15. These values were empirically established by the following relationship

$$F_1 = (1 - \sin A)^2$$

where A is angle between the dip directions of slope face and joint in case of planer and toppling failure. For wedge failure, A is the angle between plunge direction of line of intersection formed by discontinuities and slope dip direction [21].

(ii) F_2 refers to joint dip angle in the planar mode of failure. In a sense, it is a measure of the probability of joint shear strength. Its value ranges from 1.00 to 0.15. The empirically established by the following relationship

$$F_2 = \tan^2 B$$

where B is dip angle of joint for planer failure. In the wedge case, B is dip angle of plunge of line of intersection [21]. For the toppling mode of failure F_2 remains 1.00.

(iii) F_3 indicates the relationship between the slope face and joint dip. In the planar mode of failure, F_3 refers to the probability of joints day-lighted in the slope face. In case of wedge failure, F_3 indicates the relationship between the slope face and dip of plunge of intersection of two joints [21]. Conditions are favorable when slope face and joints are parallel and very unfavorable when the slope dips 10° more than joints.

The adjustment factors F_1 , F_2 and F_3 for CSMR, depends on joint-slope relationship, are calculated by using following equations proposed by Tomas *et al.* [12-14].

$$F_1 = \frac{16}{25} - \frac{3}{500} \arctan\left(\frac{1}{10}(|A| - 17)\right)$$

where, F_1 = adjustment factor,

$|A| = |\alpha_j - \alpha_s|$ for planer failure,

$|\alpha_i - \alpha_s|$ for wedge failure,

$|\alpha_j - \alpha_s - 180|$ for toppling failure, and

α_j , α_s and α_i are dip direction of joint, slope and plunge direction of line intersection of two joint planes.

$$F_2 = \frac{9}{16} + \frac{1}{195} \arctan\left(\frac{17}{100}B - 5\right)$$

where B is equals to dip (β_j) of joint for planer failure and toppling, to dip on plunge of line of intersection for wedge failure.

$$F_3 = -30 + \frac{1}{3} \arctan(C)$$

$$F_3 = -13 - \frac{1}{7} \arctan(C - 120)$$

where, C is an angular difference of dips of joint and slope ($\beta_j - \beta_s$) for planer failure. C is difference of dip of plunge of line and dip of slope ($\beta_i - \beta_s$) for wedge. For toppling, C is defined as sum of dip of joint and slope ($\beta_j + \beta_s$).

The adjustment factor for the method of excavation (F4) has been fixed empirically as follows:

Natural slopes: $F_4 = +15$, Presplitting: $F_4 = +10$,

Smooth blasting: $F_4 = +8$, Normal blasting: $F_4 = 0$,

Deficient blasting: $F_4 = -8$, and

Mechanical excavation: $F_4 = 0$.

The stability classes of SMR values, rock mass description, stability and probability of failure given by Romana [8] is also applicable for CSMR classification (**Table 2**).

5. Results and Discussion

Detailed geological investigations including structural mapping were made in the study area at Rudraprayag-Agastmuni road section along NH-109. The road cut sections of varying slope height constitute the best outcrops for determining the lithological variations, weathering conditions, and structural geological characteristics of the outcrops and rock excavation to record discontinuities and joint patterns (**Figure 3**). The study comprised of investigation of slopes at five locations which have

different lithological as well as geotechnical characteristics.

The cut slopes have steep to very steep dip angle with a developed system of joints (**Table 3**). In general, the rock mass has been covered by soil of quaternary age with scanty vegetation. Kinematic analysis indicates mainly wedge type of failure along with few toppling and planar based on the joint patterns (**Figure 4**). The joint forming planar type is not day-lighted (**Figure 4(a)**). The critical zone of failure has been shown in pink colour in stereographic projection for all five locations (**Figure 4**).

Table 2. Stability classes as per SMR values (Romana [8]).

Class	I	II	III	IV	V
SMR	81-100	61-80	41-60	21-40	0-20
Rock mass Description	Very good	Good	Normal	Bad	Very bad
Stability	Completely stable	Stable	Partially stable	Unstable	Completely unstable
Failures	None	Some block failure	Planar along some joints or many wedge failure	Planar or big wedge failure	Big planar or soil-like or circular
Probability of Failure	0.9	0.6	0.4	0.2	0

Table 3. Joints data of different locations.

	Rock type	Orientation of slope	Orientation of joints					
			J1	J2	J3	J4	J5	J6
L1	Epidiorite	70°/315°	80°/0°	80°/315°	70°/60°	65°/255°	85°/260°	45°/150°
L2	Tilwara quartzite	75°/267°	47°/80°	52°/226°	80°/60°	70°/160°	30°/10°	-
L3	Phyllite	70°/318°	81°/80°	70°/200°	75°/5°	45°/40°	47°/16°*	-
L4	Rudraprayag quartzite	80°/180°	30°/315°	52°/155°	56°/65°	-	-	-
L5	Rudraprayag metavolcanics	70°/282°	85°/30°	70°/150°	50°/250°	-	-	-



Figure 3. A cut slope section of the study area showing negative slope with 3 sets of joint.

Rock mass rating (RMR) has been calculated by five parameters namely uniaxial compressive strength (UCS), rock quality designation (RQD), spacing of discontinuities, conditions of discontinuities and ground water condition. UCS has been calculated by laboratory experiments in universal testing machine (UTM). The mean values of UCS have been used in calculation. RQD has been calculated from the relation between RQD and joint volume count (J_V) [22]. The results of required parameters for RMR classification have been given in **Table 4**. The calculation of RMR has been performed for all five locations (**Table 5**). As per the standard classification, RMR value at L1 and L4 which has rating of 71 can be classified as good rock. RMR value at L2 which has rating value of 57 can be classified as fair rock. The rock

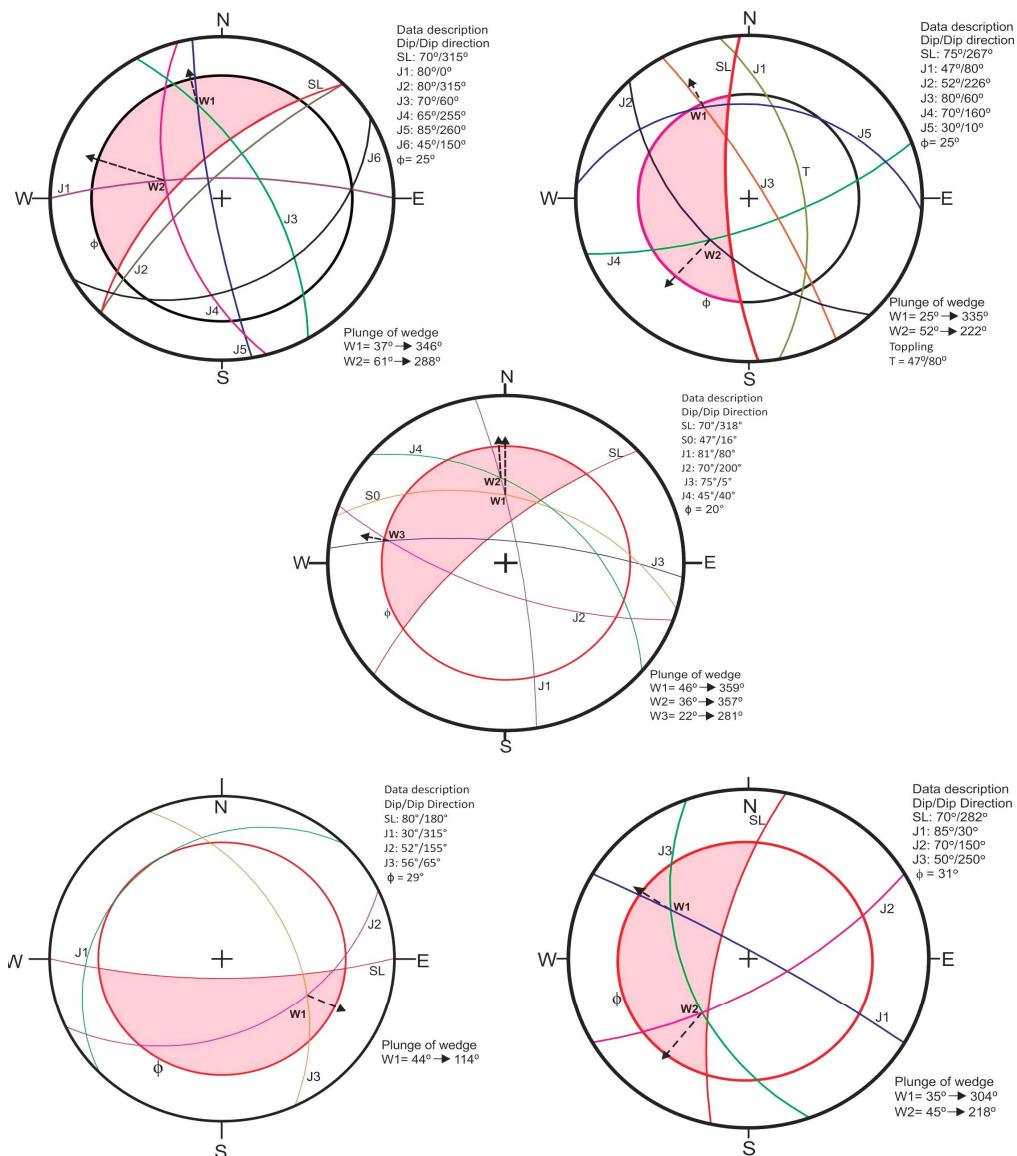


Figure 4. Plot of joints and slope at locations L1, L2, L3, L4 and L5. The pink coloured area indicates the critical zone of failure. The symbols used in figure are as SL: Slope; S0: Bedding, J1, J2, J3, J4, J5, and J6: Orientation of joints; W1, W2 and W3: Wedge formed by intersection of joints; T: Toppling.

mass with rating value of 42 may be classified as fair rock but as it is very close to the boundary between fair and poor rock so it requires special attention as well as proper care of slope. The rock mass at L5 with rating value of 82 may be classified as very good rock.

CSMR has been calculated from equation (1) using RMR values for all five locations (**Table 5**). The adjustment factors F_1 , F_2 and F_3 , based on joint-slope relationship, have been calculated from the formulae proposed by Tomas *et al.* [12-14]. The orientation of discontinuities with respect to slope forming wedge, toppling and planar type of failure in critical zone of influence as in

kinematic analysis plots (**Figure 5**). In case the two discontinuity intersecting and forming wedge in critical zone, the orientation of plunge of intersections of two discontinuities has been calculated. The wedge type of failure is common in all locations. The rock slope is being excavated using drilling and blasting technique. The uncontrolled blasting and drilling operation for excavations of slope lead to the failure of large size blocks (**Figure 6**). Blast-induced vibrations expand the zone of influence for failures replicating a controlled earthquake, affecting the stability of slope. The adjustment factor for method of excavation (F_4) is considered as deficient blasting.

Table 4. Result of geological observations required for rock mass rating (RMR).

Parameter	L1	L2	L3	L4	L5
Rock type	Epidiorite	Tilwara quartzite	Phyllite	Rudraprayag quartzite	Rudraprayag metavolcanics
Mean UCS	58 MPa	40 MPa	28 MPa	54 MPa	123 MPa
RQD (calculated from JV)*	85 %	65%	49%	80%	92%
Joint spacing	20 cm – 60 cm	20 cm – 6 cm	< 60 mm	20 cm – 6 cm	> 2 m
Joint roughness	Rough	Rough	Smooth	Slightly rough	Rough
Joint separation	0.1 - 1 mm	1 - 5 mm	1 - 5 mm	0.1 - 1 mm	1 - 5 mm
Joint persistence	3 - 10m	1 - 3 m	10 - 20 m	1 - 3 m	3 - 10m
Joint infilling	None	Soft filling >5 mm	Hardfilling >5 mm	None	None
Weathering	Slightly weathered	Moderately weathered	Slightly weathered	Slightly weathered	Unweathered
Ground water condition	Dry	Dry	Dry	Dry	Dry

Table 5. Rock Mass Rating (RMR) at different locations.

Parameter	L1	L2	L3	L4	L5
Rock type	Epidiorite	Tilwara quartzite	Phyllite	Rudraprayag quartzite	Rudraprayag metavolcanics
UCS Rating	7	4	4	7	12
RQD Rating	17	13	8	17	20
Joint spacing Rating	10	8	5	10	15
Joint condition Rating*	2 + 4 + 5 + 6 + 5 = 22	4 + 1 + 5 + 4 + 3 = 17	1 + 1 + 1 + 2 + 5 = 10	4 + 4 + 3 + 6 + 5 = 22	2 + 4 + 5 + 6 + 6 = 23
Ground water Rating	15	15	15	15	15
RMR	71	57	42	71	85

**Figure 5. Very closed space jointed phyllitic rock with higher persistency.**

The influence of orientation of joints and method of excavation of slopes has been applied for final modification of the rock mass rating value. The continuous slope mass rating (CSMR) has been calculated for wedge and

**Figure 6. Large size rock blocks failure due to blasting.**

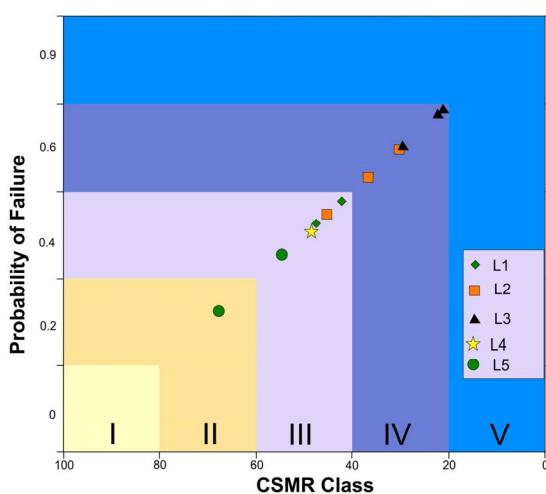
toppling failures for all five locations (**Table 6**). As per the standard classification, the values of CSMR at L1 (Epidiorite rock) shows values 47 and 42 for W1 and W2 respectively. The slope may be classified in class III as partially stable. At location L2, Tilwara quartzite rock

Table 6. Results of continuous slope mass rating (CSMR).

	RMR	Slope orientation	Feature	Dip	Dip direction	F1	F2	F3	F4	CSMR	Class/ Stability
L1	71	70°/315°	W1	37°	346°	0.31	0.83	59.42	-8	47.55	III/ Partially stable
			W2	61°	288°	0.37	0.97	57.89		42.23	III/ Partially stable
			T	47°	80°	0.91	0.93	22.06		30.34	IV/ Unstable
L2	57	75°/267°	W1	25°	335°	0.17	0.37	59.62	-8	45.22	III/ Partially stable
			W2	52°	222°	0.22	0.95	59.17		36.76	IV/ Unstable
			W1	46°	359°	0.24	0.92	59.20		21.11	IV/ Unstable
L3	42	70°/318°	W2	36°	357°	0.25	0.81	59.44	-8	22.13	IV/ Unstable
			W3	22°	281°	0.26	0.30	59.60		29.39	IV/ Unstable
L4	71	80°/180°	W1	44°	114°	0.27	0.91	59.47	-8	48.55	III/ Partially stable
L5	85	70°/282°	W1	35°	304°	0.48	0.79	59.45	-8	54.55	III/ Partially stable
			W2	45°	218°	0.17	0.92	59.24		67.64	II/ Stable

with one toppling and two wedges (W1 and W2) having CSMR values 30, 45 and 37 respectively. The slope is unstable in case of toppling and W2 but partially stable for W1.

During field investigations and petrographic study, it has been observed that Tilwara quartzites rock is more deformed and crushed grains in internal atomic arrangement that shows protomylonitic behavior under microscope. So it is considered in class IV. At L3, phyllite rock with three wedges with CSMR values 21, 22 and 29 respectively. The slope can be classified under class IV as unstable. At L4, Haryali quartzite with CSMR value 48 may be classified in class III as partially stable. At L5, Rudraprayag Metavolcanics with two wedge (W1 and W2) and CSMR values 51 and 65. Slope may be classified as partially stable for W1 and stable for W2. The observation from field indicating that slope at L5 is stable. The CSMR values obtained for all five locations have been plotted in CSMR class- Probability of failure chart based on Romana standard classification of SMR [8] (Figure 7).

**Figure 7. The plot of CSMR values of five different locations.**

6. Conclusions

The rock mass classifications are very significant tool for characterization of rock mass especially for slope vulnerability assessment. The slope mass rating is the most comprehensive and widely used technique for rock slope assessment. The Continuous SMR system seems to be more sensitive to the slope characteristics and yields finer rating values than does the discrete SMR system. The five slopes have been studied in Himalayan region along NH-109 cut slopes and the values of CSMR indicate that phyllite and Tilwara quartzite slopes are more vulnerable as compared to Haryali quartzite and Epidiorite slopes. These slopes required immediate treatment to avoid any kind of mis-happening due to slope failure. Further, the results of continuous slope mass rating is closely matching with the field observations. This technique may be helpful for rapid investigation of slopes in deformed hilly terrains.

7. Acknowledgements

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